NITROGEN MANAGEMENT

Nitrogen Fertilization and Rotation Effects on No-Till Dryland Wheat Production

Ardell D. Halvorson,* David C. Nielsen, and Curtis A. Reule

ABSTRACT

No-till (NT) production systems, especially winter wheat (*Triticum aestivum* L.)–summer crop–fallow, have increased in the central Great Plains, but few N fertility studies have been conducted with these systems. Therefore, winter wheat (W) response to N fertilization in two NT dryland crop rotations, wheat–corn (*Zea mays* L.)–fallow (WCF) and wheat–sorghum (*Sorghum bicolor* L.)–fallow (WSF), on a Platner loam (fine, smectitic, mesic Aridic Paleustoll) was evaluated for 9 yr. Five N rates, 0, 28, 56, 84, and 112 kg N ha^{-1}, were applied to each rotation crop. Wheat biomass and grain yield response to N fertilization varied with year but not with crop rotation, increasing with N application each year, with maximum yields being obtained with 84 kg N ha^{-1} over all years. Based on grain N removal, N fertilizer use efficiency (NFUE) varied with N rate and year, averaging 86, 69, 56, and 46% for the 28, 56, 84, and 112 kg ha^{-1} N rates, respectively. Grain protein increased with increasing N rate. Precipitation use efficiency (PUE) increased with N addition, leveling off above 56 kg N ha^{-1}. A soil plus fertilizer N level of 124 to 156 kg N ha^{-1} was sufficient to optimize winter wheat yields in most years in both rotations. Application of more than 84 kg N ha^{-1} on this Platner loam soil, with a gravel layer below 120 cm soil depth, would more than likely increase the amount of NO_3–N available for leaching and ground water contamination. Wheat growers in the central Great Plains need to apply N to optimize dryland wheat yields and improve grain quality, but need to avoid over-fertilization with N to minimize NO_3–N leaching potential.

In the central Great Plains region of the USA, use of reduced tillage and NT systems increased during the 1990s. These tillage systems improved the storage of precipitation in the soil profile compared with mechanical tillage systems, allowing more intensive cropping systems to be developed (Anderson et al., 1999; Halvorson and Reule, 1994; Halvorson et al., 2002; McGee et al., 1997; Nielsen et al., 2002; Peterson et al., 1996). The dominant wheat–fallow system of farming is being slowly replaced with more intensive cropping systems, such as 3-yr WCF and WSF systems, 4-yr systems (crop–crop–crop–fallow), and annual cropping systems with no fallow (Anderson et al., 1999; Halvorson and Reule, 1994; Norwood, 2000; Peterson et al., 1993; Schlegel et al., 2002).

Dhuyvetter et al. (1996) reported that the more intensive cropping systems had higher profit potential than wheat–fallow systems in the Great Plains. This finding was supported by the economic analyses of intensive dryland cropping systems in eastern Colorado (Kaan et al., 2002) and in south-central North Dakota (DeVuyst and Halvorson, 2004). Greater profit potential with increasing cropping intensity and NT production systems has enhanced the adoption of these systems.

Crop water use efficiency is improved with more intensive cropping systems (Halvorson, 1990; Nielsen et al., 2002; Norwood, 1999; Farahani et al., 1998). Nitrogen fertilization can improve water use efficiency, but high N fertilization rates can result in excess biomass production, which uses up stored soil water needed for grain production (Nielsen and Halvorson, 1991). Therefore, it is important to balance N fertilization with available seasonal water supplies.

More intensive cropping systems using NT may require higher rates of N fertilizer to maintain yield potential due to increased crop N removal as well as compensate for N sequestration in crop residue and surface soil due to lack of tillage. Few N fertility rate studies have been conducted in the central Great Plains under NT conditions to evaluate the response of winter wheat to N application in more intensive NT cropping systems (Halvorson and Reule, 1994; Kolberg et al., 1996; Thompson and Whitney, 1998). Halvorson and Reule (1994) reported spring barley (*Hordeum vulgare* L.) yields were optimized with the application of 67 kg N ha^{-1} each crop year in a NT annual cropping system on a Weld silt loam (fine, smectitic, mesic Aridic Argiustoll). Thompson and Whitney (1998) reported that 67 kg N ha^{-1} applied to each crop was sufficient to optimize wheat and sorghum yields on a silt loam soil in Kansas. Kolberg et al. (1996) reported no yield benefits to N applications above 84 kg N ha^{-1} on dryland winter wheat in WCF and WSF rotations on two loam soils in eastern Colorado.

The objective of this study was to evaluate the influence of N fertilization rate and crop rotation (WCF and WSF) on dryland winter wheat yields, NFUE, PUE, and residual soil NO_3–N using a NT production system on a Platner loam soil with a gravelly layer below the 120-cm depth.

A.D. Halvorson, USDA-ARS, 2150 Centre Ave, Bldg. D, Suite 100, Fort Collins, CO 80526; D.C. Nielsen, USDA-ARS, Central Great Plains Res. Stn., 40335 County Road GG, Akron, CO 80720; and C.A. Reule, USDA-ARS, 2150 Centre Ave., Bldg. D, Suite 100, Fort Collins, CO 80526. Contribution from USDA-ARS. The U.S. Department of Agriculture offers its programs to all eligible persons regardless of race, color, age, sex, or national origin, and is an equal opportunity employer. Received 18 Dec. 2003. *Corresponding author (ardell.halvorson@ars.usda.gov).

Published in Agron. J. 96:1196–1201 (2004).

677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: NFUE, nitrogen fertilizer use efficiency; NT, no-till; PUE, precipitation use efficiency; WCF, wheat–corn–fallow; WSF, wheat–sorghum–fallow.

MATERIALS AND METHODS

The study was initiated in 1984 on a Platner loam (fine, smectitic, mesic Aridic Paleustoll) at the Central Great Plains Research Station (40°9′ N, 103°9′ W) at Akron, CO. This soil had a coarse gravelly layer below the 120-cm depth, which had very low water holding capacity. The experimental treatments consisted of a factorial combination of five N rates and two crop rotations (WCF and WSF) in a split-plot, randomized complete block design with four replications. The main plots were N rate (0, 28, 56, 84, and 112 kg N ha^{-1}) with crop rotation as subplots. Three sets of these plots were initiated in the fall of 1984 so that each phase (WCF [sequence A], CFW [sequence B], FWC [sequence C] or WSF [sequence A], SFW [sequence B], FWS [sequence C]) of each crop rotation was present each year. The main plots were 9.2 by 12.2 m with the subplots being 4.6 by 12.2 m. The wheat phase of the study was conducted from 1985 through 1993.

Anhydrous ammonia (NH_3) was applied as the N source from 1985 to 1987 just before planting of each crop in the rotation. From 1988 through 1993, NH_4NO_3 was broadcast on the soil surface with no incorporation just before planting each crop in the rotation. At study initiation, a blanket application (56 kg P ha^{-1}) of triple superphosphate was broadcast applied to all plots. From 1991 to 1993, 15 kg P ha^{-1} was band applied with the wheat seed at planting.

Winter wheat (c.v. 'TAM 105' [1985 and 1986] or 'TAM 107' [1987–1993]) was planted each year in late September at a seeding rate of about 2.2 million seeds ha^{-1} with a NT hoe drill with a 30-cm row spacing (1985–1988) or NT disk drill with 18-cm row spacing (1989–1993). Herbicides were used during the fallow period to control weed growth. The plots were generally weed free during the wheat production period with no herbicide applied for weed control. The wheat was harvested in early to mid-July each year from the center of each plot. Wheat yields are expressed on a 120 g kg^{-1} water content basis. Precipitation and pan evaporation data were collected at the long-term weather station located about 850 m from the plot area.

Soil samples, one 3-cm diameter core per plot, were collected in 30-cm increments to a depth of 120 cm from each treatment before planting and after harvest of wheat for gravimetric water content and NO_3–N analysis. Soil bulk density was used to calculate water content of the soil. Soil crop water use was estimated by subtracting the harvest soil water content from the planting soil water content. Estimated total water use by each crop was assumed to be soil water use plus growing season precipitation. During the study, no visual signs of runoff of precipitation from the plots were observed; therefore, loss of growing season precipitation to runoff or drainage was assumed to be negligible. The air-dried soil samples were ground to pass a 2-mm sieve before analysis for NO_3–N content. Soil NO_3–N was determined by Cd reduction with an autoanalyzer (Lachat Instruments, 1989) on a 5:1 extract/soil ratio using a 0.01 *M* $CaSO_4$ extracting solution.

Total biomass samples were collected from at least a 2-m^2 area in each plot at harvest for yield and N determination. All grain yields were determined by harvesting a minimum of 15 m^2 area from each plot with a plot combine. The plant samples were oven-dried, ground to pass a 0.85-mm sieve before analysis for N content. Biomass and grain samples were analyzed for total N content using a micro-Kjeldahl N digestion (Isaac and Johnson, 1976) and Technicon[1] autoanalyzer procedure (Technicon, 1973). Grain protein was estimated by multiplying grain N content (%) by 5.7 (Horwitz, 1960).

Nitrogen fertilizer use efficiency (NFUE) was estimated for each N rate treatment by subtracting the average grain N uptake of the check plot (no fertilizer N applied) from the grain N uptake of each N rate and dividing this difference by the specific N rate. Precipitation use efficiency (PUE) was estimated by dividing grain yield (kg ha^{-1}) by the amount (mm) of growing season (April–June) precipitation.

Analyses of variance were performed using Analytical Software[1] Statistix7 program (Analytical Software, 2000) to determine treatment effects. All statistical comparisons were made at the $\alpha = 0.05$ probability level unless otherwise stated using least significant difference method for mean separation. If the analysis of variance indicated a significant *F* value for N, a linear or quadratic function was fit to the N response data using regression functions present in the graphics program (SigmaPlot version 7.0, SPSS Inc., Chicago, IL[1]).

[1] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the authors or the USDA-ARS.

Table 1. Monthly, annual, and growing season (April–June) precipitation and growing season pan evaporation at the study site (Akron, CO) from 1985 through 1993, and the 87-yr average precipitation.

Month	Year 1985	1986	1987	1988	1989	1990	1991	1992	1993	87-yr avg.
	precipitation, mm									
Jan.	12	3	9	38	14	19	2	14	6	8
Feb.	5	28	37	7	12	4	4	5	14	9
Mar.	8	7	28	30	5	43	28	50	12	21
Apr.	58	51	12	18	13	38	21	5	49	43
May	85	56	113	129	24	104	104	38	26	76
June	33	97	58	51	105	24	53	98	44	63
July	115	8	65	65	51	120	80	51	122	69
Aug.	24	24	101	37	84	112	26	102	23	52
Sept.	60	20	30	25	25	18	3	1	21	31
Oct.	22	26	10	0	5	27	10	21	94	23
Nov.	19	7	22	3	1	20	37	19	26	14
Dec.	15	9	16	9	5	2	11	6	12	11
Annual total	455	336	501	412	344	531	379	410	449	419
Apr.–June total	176	204	183	198	142	166	178	141	119	182
	pan evaporation, mm									
April	185	137	237	172	210	160	165	210	149	
May	218	209	182	251	290	211	248	297	218	
June	294	267	261	296	237	361	316	260	269	
Apr.–June total	698	614	680	720	738	732	729	767	636	
PE–Precip.	522	410	497	522	596	566	551	626	517	

Table 2. Total soil water and NO_3–N at winter wheat planting in the 0- to 120-cm soil depth, averaged over wheat–corn–fallow and wheat–sorghum–fallow rotations.

	N rate, kg N ha^{-1}					
Year	0	28	56	84	112	Yearly avg.
	soil water, mm (0- to 120-cm depth)					
1985	299a†	299a	299a	299a	299a	299cd‡
1986	292a	292a	292a	292a	292a	292cd
1987	269a	284a	258a	251a	268a	266b
1988	299a	259a	280a	325a	314a	295cd
1989	283a	315a	345a	298a	296a	307d
1990	258ab	264a	232bc	227c	253abc	247a
1991	300a	245a	280a	297a	292a	282bc
1992	277a	298a	320a	269a	258a	284bc
1993	304a	310a	293a	287a	300a	299cd
Avg.	287a	285a	289a	283a	286a	
	soil NO_3–N, kg N ha^{-1} (0- to 120-cm depth)					
1985	50a†	50a	50a	50a	50a	50ab‡
1986	36a	36a	36a	36a	36a	36a
1987	95a	185a	164a	215a	377b	207f
1988	49a	60ab	59ab	113c	96bc	75c
1989	91a	87a	93a	83a	102a	91cd
1990	92a	92a	182ab	201ab	267b	167e
1991	59a	96a	92a	100a	113a	92cd
1992	43a	53ab	77b	59ab	126c	71bc
1993	65a	67a	108ab	145b	155b	108d
Avg.	64a	81ab	95ab	111b	147c	

† Values within a row followed by the same letter are not significantly different for N rates.

‡ Values within the yearly average column followed by the same letter are not significantly different.

RESULTS AND DISCUSSION

Annual precipitation during the study period varied considerably with year (Table 1). Above average annual precipitation occurred in 1985, 1987, 1990, and 1993, about average in 1988 and 1992, and below average in 1986, 1989, and 1991. Growing season (April–June) precipitation, however, did not follow the same pattern as for annual precipitation (Table 1). Growing season precipitation was below the long-term average in 1989, 1990, 1992, and 1993, near average in 1985, 1987, and 1991, and above average in 1986 and 1988. Soil water in the 0- to 120-cm root zone at wheat planting was probably near field capacity most years, with 1987 and 1990 having slightly lower water contents than the other years (Table 2). Thus, growing season precipitation and climatic conditions, such as temperature, evapotranspiration, frost, and hail, were the elements other than N fertilization having the greatest impact on wheat yields during the study period.

Total biomass production was not significantly affected by crop rotation, with average wheat biomass production of 7596 and 7666 kg ha^{-1} for the WCF and WSF rotations, respectively. Biomass production varied with year and N rate (Fig. 1, with yields for each crop sequence shown separately for easier reader interpretation). Biomass was increased by N application each year, but the N rate resulting in maximum biomass yield varied with year (Table 3). The highest level of biomass production occurred in 1986, 1991, and 1993 with the 84 or 112 kg N ha^{-1} N rates resulting in maximum yield. In 1985, 1987, and 1988, biomass yields were slightly lower but were still near maximum with the two highest N rates. Biomass yields tended to be lowest in 1989, 1990,

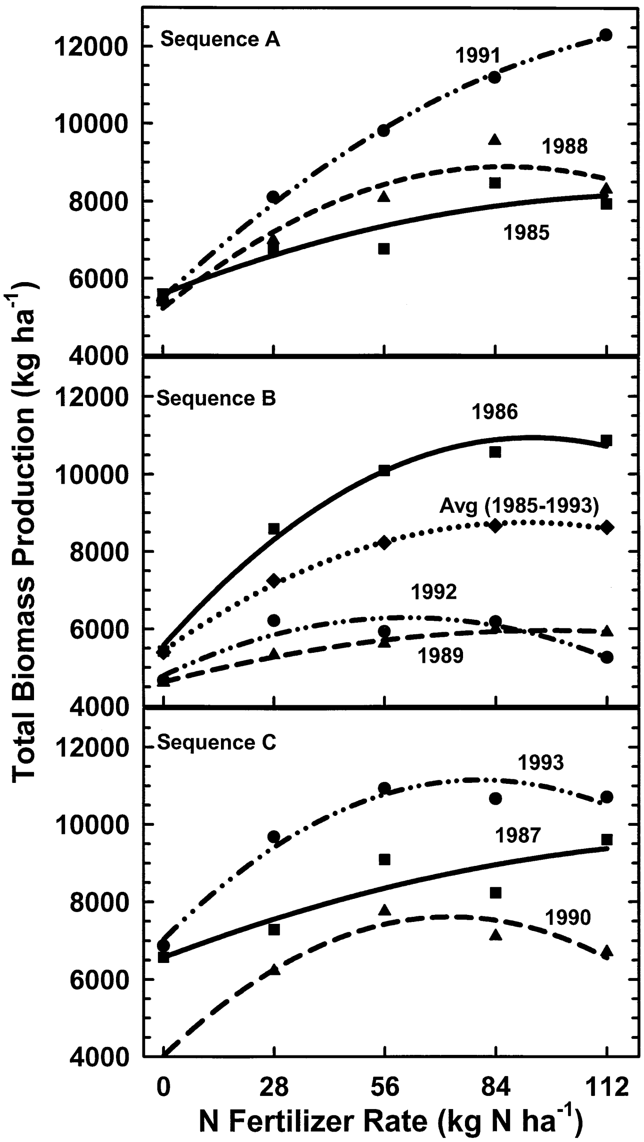

Fig. 1. Total winter wheat biomass production each year at crop maturity for each of the three cropping sequences as a function of N fertilizer rate, averaged over wheat–corn–fallow and wheat–sorghum–fallow rotations.

and 1992, with biomass production being near maximum with the 28 or 56 kg ha^{-1} N rates.

Grain yields varied significantly with year and N application rate (Fig. 2 and Table 3), but not with crop rotation. Grain yields averaged 3281 and 3275 kg ha^{-1} for the WCF and WSF, respectively. Norwood (2000) also found no differences in wheat grain yields between WCF and WSF rotations. Grain yield in 1985, 1986, and 1991 increased with increasing N rate, maximizing at the 84 and 112 kg ha^{-1} N rates. In 1988, 1990, and 1993, grain yields were near maximum at the 56 and 84 kg ha^{-1} N rates. Low grain yield in 1988 probably resulted due to low rainfall during April through mid-May, high evaporative demands, and a large number of days with high air temperatures, even with slightly better than average growing season precipitation. Butler et al. (2001) showed a strong decline in winter wheat yields with daily maximum temperatures >25°C between 21 May

Table 3. Regression equations for the winter wheat biomass and grain yields shown in Fig. 1 and 2 as a function of N fertilizer rate, averaged over wheat–corn–fallow and wheat–sorghum–fallow rotations.

Year	†Equation: $y = a + bx + cx^2$ a	b	c	r^2	Predicted maximum yield kg ha^{-1}	N rate, kg ha^{-1}
			Total biomass			
1985	5 588	40.3	−0.157	0.85	8 174	128
1986	5 570	115.0	−0.616	0.99	10 937	93
1987	6 568	38.6	−0.121	0.81	9 646	160
1988	5 211	84.8	−0.488	0.93	8 895	87
1989	4 619	27.3	−0.140	0.99	5 950	98
1990	4 023	98.7	−0.679	0.96	7 610	73
1991	5 496	95.9	−0.318	1.00	12 726	151
1992	4 789	49.2	−0.403	0.84	6 291	61
1993	7 029	102.9	−0.643	0.97	11 146	80
Avg.	5 432	72.5	−0.396	1.00	8 750	92
			Grain			
1985	2 687	18.5	−0.055	0.93	4 243	168
1986	2 626	39.9	−0.184	1.00	4 789	108
1987	2 963	17.8	−0.108	0.59	3 696	82
1988	1 733	26.1	−0.174	0.89	2 712	75
1989	2 288	17.4	−0.126	0.87	2 889	69
1990	1 523	40.8	−0.263	0.92	3 105	78
1991	2 616	47.6	−0.240	0.99	4 976	99
1992	2 461	33.0	−0.250	0.86	3 550	66
1993	2 297	52.2	−0.325	0.95	4 393	80
Avg.	2 355	32.6	−0.192	0.99	3 739	85

† y = biomass or grain yield, kg ha^{-1}; x = N rate, kg N ha^{-1}.

and 1 July. In 1988, 34 d had maximum temperatures >25°C, compared with the 1985–1993 average of 25 d. Frost (on 29 and 30 April and on 2, 4, 9, and 10 May) and hail (14 June) were responsible for low grain yields in 1990 and lack of response to N rates above 56 kg N ha^{-1}. Grain yields leveled off above 56 kg ha^{-1} N rate in 1993 due to lack of water to complete grain fill at the highest N rates, but yields were excellent compared with other years. Growing season precipitation in 1993 was the lowest during the study, but pan evaporation was also low. Soil water use from the 120-cm profile was highest in 1993 (164 mm), which contributed to the excellent grain yields. Soil water use for the other years was 117, 82, 82, 96, 101, 92, 109, and 97 mm for 1985, 1986, 1987, 1988, 1989, 1990, 1991, and 1992, respectively. As reported by Nielsen and Halvorson (1991), excess N can create a large plant and biomass production that uses up water needed for grain production. In 1987, 1989, and 1992, grain yields were at near maximum with the 28 kg ha^{-1} N rate. In 1989 and 1992, growing season precipitation was low and pan evaporation was high (Table 1), which created water stress on the plants. Total biomass was also low for these 2 yr (Fig. 1). A frost on 26 May also damaged the 1992 wheat crop, which was headed, contributing to the low yield. In 1987, residual soil N was very high (Table 2) in all plots at wheat planting; therefore, response to N was limited to the lower N fertilizer rate. The average grain production over the nine wheat crops was 2316, 3201, 3560, 3681, and 3633 kg ha^{-1} for the 0, 28, 56, 84, and 112 kg ha^{-1} N rates, respectively. Thus, when averaged over all years and climates, grain yields on this Platner loam soil were near maximum with the application of 84 kg N ha^{-1}. This is consistent with the N requirements reported by

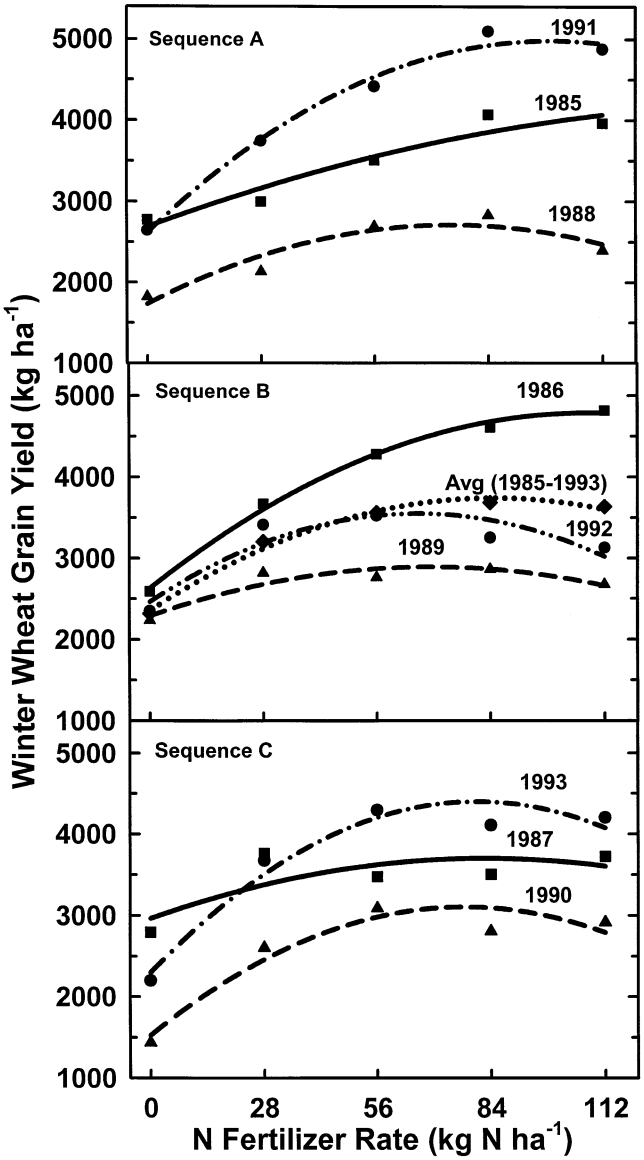

Fig. 2. Winter wheat grain yield each year for each of the three cropping sequences as a function of N fertilizer rate, averaged over wheat–corn–fallow and wheat–sorghum–fallow rotations.

Kolberg et al. (1996) for optimizing winter wheat yields in NT WCF and WSF systems.

Assuming that farmers, fertilizer dealers, or crop consultants would sample soil to at least a 60-cm depth, we developed an exponential relationship between soil N (0–60 cm) plus fertilizer N applied and relative grain yield each year (Fig. 3). A soil plus fertilizer N level of 156 kg N ha^{-1} was needed to achieve a 95% yield potential over the 9 yr of this study. Using the approach of Halvorson and Reule (1994), we plotted relative grain yield vs. soil N (0–60 cm) plus fertilizer N applied for only those N levels at or below 100% relative yield potential (Fig. 4). The quadratic response curve shows that 124 kg N ha^{-1} was needed to achieve 95% grain yield potential over the 9-yr period. These N requirements for winter wheat are slightly lower than those found for barley and wheat in an annual cropping system reported by Halvorson and Reule (1994) on a Weld silt

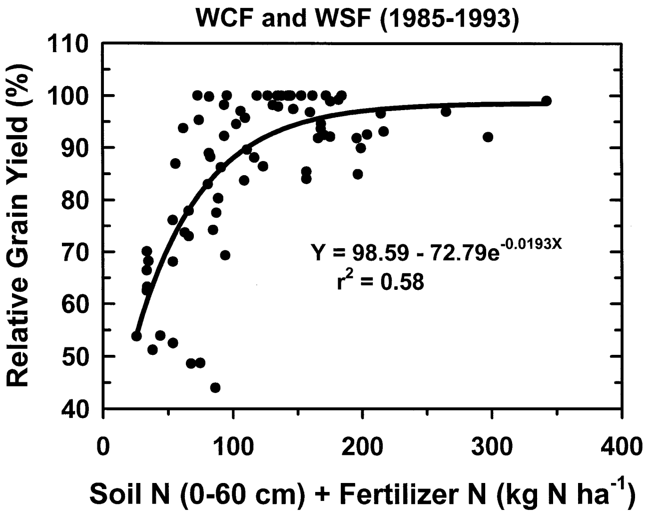

Fig. 3. Relative winter wheat grain yield as a function of soil NO_3–N (0- to 60-cm depth) plus fertilizer N rate across all years and crop rotations.

loam soil with a deeper soil profile. Schlegel et al. (2003) reported a N requirement of 127 kg N ha^{-1} for optimum winter wheat yields in western Kansas.

Grain protein content generally increased with increasing N level, but varied with year (Table 4). The protein values in Table 4 are expressed on an oven-dry basis; therefore, they are slightly higher than if expressed on 120 g kg^{-1} water content basis similar to grain yield. Averaged over the 9 yr, grain protein increased significantly with increasing N rate, with the highest protein level being with the highest N rate.

The amount of N removed in the grain each year generally increased with increasing N rate, but the amount of N removed in the grain varied with year and grain yield (Table 5). Averaged over all years, grain yield increased significantly with increasing N rate. Nitrogen fertilizer use efficiency (NFUE) was generally highest

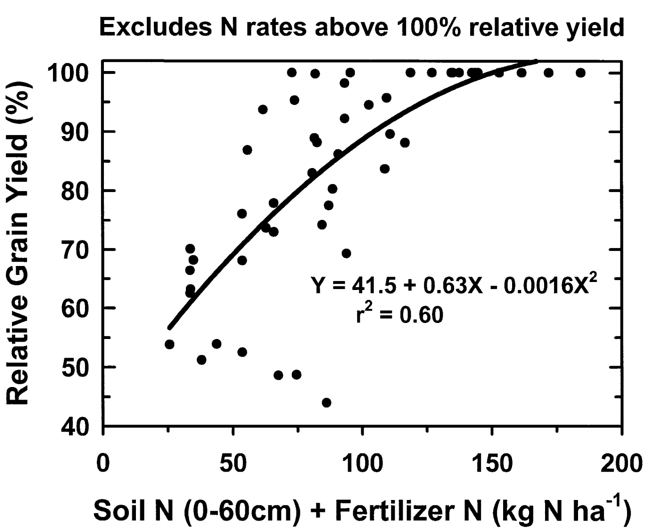

Fig. 4. Relative winter wheat grain yield as a function of soil NO_3–N (0- to 60-cm depth) plus fertilizer N rate across all years and crop rotations, excluding N levels above 100% of maximum yield each year.

Table 4. Grain protein concentration as a function of N rate at maturity on an oven-dry basis, averaged over wheat–corn–fallow and wheat–sorghum–fallow rotations.

	N rate, kg N ha^{-1}					†Equation: $y = a + bx + cx^2$			
Year	0	28	56	84	112	a	b	c	r^2
	— grain protein, g kg^{-1} —								
1985	79	97	98	108	124	81.1	0.317	0.0005	0.95
1986	88	101	98	110	118	89.8	0.197	0.0005	0.91
1987	122	152	173	154	177	125.7	0.931	−0.0048	0.76
1988	122	131	156	157	167	120.5	0.633	−0.0020	0.94
1989	145	163	184	190	184	143.4	1.012	−0.0057	0.98
1990	105	116	150	165	186	101.8	0.769	−0.0001	0.98
1991	112	141	150	165	168	113.2	0.959	−0.0043	0.98
1992	111	133	153	171	168	108.9	1.069	−0.0046	0.99
1993	85	100	129	157	173	82.0	0.828	0.0001	0.99
Avg.	108	126	143	153	163	107.4	0.746	−0.0023	1.00

† y = grain protein, g kg^{-1}; x = N rate, kg N ha^{-1}.

at the 28 kg ha^{-1} N rate and lowest at the 112 kg ha^{-1} N rate (Table 5). At the 28 kg N ha^{-1} fertilizer rate, NFUE exceeded 100% in 4 of the 9 yr, indicating that more N was taken up in the grain than applied with the fertilizer. The NFUE varied with year and N rate. When averaged over all years, NFUE decreased as the amount of N fertilizer applied increased. At the 84 kg N ha^{-1} fertilizer rate, which had the highest average grain yield, NFUE averaged 56%. At the 56 kg N ha^{-1} fertilizer rate, grain yields were 97% of the average maximum yield and had a NFUE of 69%.

Precipitation use efficiency (PUE) varied with year and N rate (Table 6), generally increasing with N application, but tending to level off above 56 kg N ha^{-1} fertilizer rate. The PUE data reflect the same trends as for grain yield, since precipitation did not vary with N rate. When averaged over all years, PUE increased with increasing N rate up to 56 kg N ha^{-1} and then leveled off.

Table 5. Winter wheat grain N removal and N fertilizer use efficiency based on grain N removal, averaged over wheat–corn–fallow and wheat–sorghum–fallow rotations.

	N rate, kg N ha^{-1}					†Equation: $y = a + bx + cx^2$			
Year	0	28	56	84	112	a	b	c	r^2
	– grain N uptake, kg N ha^{-1} –								
1985	38	50	59	76	84	37.5	0.430	−0.00004	0.99
1986	31	51	57	70	78	32.6	0.568	−0.0015	0.98
1987	52	87	91	82	101	57.4	0.808	−0.0042	0.74
1988	32	44	63	68	60	29.8	0.839	−0.0050	0.95
1989	49	71	78	83	75	49.8	0.841	−0.0055	0.99
1990	23	46	71	71	83	23.2	1.001	−0.0043	0.97
1991	46	80	102	130	126	44.7	1.464	−0.0064	0.98
1992	40	70	83	86	82	41.0	1.146	−0.0071	0.99
1993	29	57	85	99	112	28.1	1.214	−0.0042	1.00
Avg.	38	62	77	85	89	38.2	0.923	−0.0042	1.00
	—— NFUE, % ——								
1985	–	44	38	46	42	45.4	−0.098	0.0007	0.03
1986	–	69	46	45	42	95.9	−1.158	0.0061	0.94
1987	–	126	70	36	44	218.6	−3.833	0.0202	1.00
1988	–	43	56	42	25	20.5	1.116	−0.0097	0.94
1989	–	75	50	40	23	99.0	−0.948	0.0025	0.98
1990	–	83	86	57	54	92.2	−0.159	−0.0019	0.82
1991	–	124	100	100	72	133.0	−0.377	−0.0013	0.90
1992	–	105	76	55	37	139.3	−1.328	0.0037	1.00
1993	–	100	101	84	74	99.7	0.159	−0.0036	0.93
Avg.	–	86	69	56	46	104.8	−0.736	0.0019	1.00

† y = grain N uptake, kg N ha^{-1} or N fertilizer use efficiency (NFUE), %; x = N rate, kg N ha^{-1}.

Table 6. Growing season precipitation use efficiency (PUE) by winter wheat each year as a function of N fertilization rate, averaged over wheat–corn–fallow and wheat–sorghum–fallow rotations.

Year	N rate, kg N ha^{-1}					†Equation: $y = a + bx + cx^2$			
	0	28	56	84	112	a	b	c	r^2
	PUE, kg grain ha^{-1} mm precipitation^{-1}								
1985	15.8	17.0	19.9	23.1	22.5	15.3	0.104	−0.0003	0.93
1986	12.7	18.0	21.0	22.6	23.6	12.9	0.196	−0.0009	1.00
1987	15.3	20.6	19.0	19.2	20.3	16.2	0.098	−0.0006	0.59
1988	9.2	10.8	13.6	14.3	12.1	8.8	0.131	−0.0009	0.89
1989	15.7	19.9	19.5	20.1	18.9	16.1	0.123	−0.0009	0.87
1990	8.6	15.7	18.6	16.9	17.6	9.2	0.246	−0.0016	0.92
1991	14.9	21.1	24.8	28.7	27.4	14.7	0.268	−0.0014	0.99
1992	16.7	24.2	25.0	23.0	22.2	17.5	0.234	−0.0018	0.86
1993	18.5	30.9	36.1	34.5	35.3	19.3	0.439	−0.0027	0.95
Avg.	14.1	19.8	21.9	22.5	22.2	14.4	0.204	−0.0012	0.99

† y = Precipitation use efficiency (PUE), kg grain ha^{-1} mm precipitation^{-1}; x = N rate, kg N ha^{-1}.

SUMMARY

This study shows that N fertilization of winter wheat in a WCF or WSF system is essential to optimize grain yield potential. On this Platner loam soil with gravel layer below the 120-cm depth, application of 112 kg N ha^{-1} appears to be an excessive rate for the amount of water available to the wheat crop. Grain protein was increased by increasing N fertilizer rate, but this varied with year. Nitrogen fertilizer use efficiency generally decreased with increasing N rate, varying with year. Precipitation use efficiency was lowest with no N fertilizer applied, and generally increased with increasing N rate up to 56 kg N ha^{-1}, then leveled off with increasing N rate. The results indicate that a soil plus fertilizer N level of between 124 and 156 kg N ha^{-1} would be sufficient to produce a 95% yield potential. The study shows that wheat grain yields and protein content will be improved by N fertilization, but soil testing to monitor residual soil NO_3–N levels is needed to prevent overfertilization with N.

REFERENCES

Analytical Software. 2000. Statistix7 user's manual. Analytical Software, Tallahassee, FL.

Anderson, R.L., R.A. Bowman, D.C. Nielsen, M.F. Vigil, R.M. Aiken, and J.G. Benjamin. 1999. Alternative crop rotations for the Central Great Plains. J. Prod. Agric. 12:95–99.

Butler, J.D., P.F. Byrne, D.C. Nielsen, N.J. Doesken, G.S. McMaster, S.D. Haley, and C. Stushnoff. 2001. Determining temperature and precipitation variables that best explain Colorado wheat yields. *In* Annual Meetings Abstracts [CD-ROM]. ASA, CSSA, and SSSA, Madison, WI.

DeVuyst, E.A., and A.D. Halvorson. 2004. Economics of annual cropping versus crop–fallow in northern Great Plains as influenced by tillage and nitrogen. Agron. J. 96:148–153.

Dhuyvetter, K.C., C.R. Thompson, C.A. Norwood, and A.D. Halvorson. 1996. Economics of dryland cropping systems in the Great Plains: A review. J. Prod. Agric. 9:216–222.

Farahani, H.J., G.A. Peterson, and D.G. Westfall. 1998. Dryland cropping intensification: A fundamental solution to efficient use of precipitation. Adv. Agron. 64:197–223.

Halvorson, A.D. 1990. Cropping systems and N fertilization for efficient water use in the central Great Plains. Great Plains Agric. Council Bull. 131:117–123.

Halvorson, A.D., G.A. Peterson, and C.A. Reule. 2002. Tillage system and crop rotation effects on dryland crop yields and soil carbon in the Central Great Plains. Agron. J. 94:1429–1436.

Halvorson, A.D., and C.A. Reule. 1994. Nitrogen fertilizer requirements in an annual dryland cropping system. Agron. J. 86:315–318.

Horwitz, W. (ed.) 1960. Official methods of analysis of the AOAC. 9th ed. p. 169. AOAC, Washington, DC.

Isaac, R.A., and W.C. Johnson. 1976. Determination of total nitrogen in plant tissue, using a block digester. J. Assoc. Off. Anal. Chem. 59:98–100.

Kaan, D.A., D.M. O'Brien, P.A. Burgener, G.A. Peterson, and D.G. Westfall. 2002. An economic evaluation of alternative crop rotations compared to wheat–fallow in northeastern Colorado. Tech. Bull. TB02–1. Colorado State Univ., Fort Collins.

Kolberg, R.L., N.R. Kitchen, D.G. Westfall, and G.A. Peterson. 1996. Cropping intensity and nitrogen management impact of dryland no-till rotations in the semi-arid western Great Plains. J. Prod. Agric. 9:517–522.

Lachat Instruments. 1989. Nitrate in 2 *M* KCl soil extracts. Quik Chem Method no. 12-107-04-1-B. Lachat Instruments, Milwaukee, WI.

McGee, E.A., G.A. Peterson, and D.G. Westfall. 1997. Water storage efficiency in no-till dryland cropping systems. J. Soil Water Conserv. 52:131–136.

Nielsen, D.C., and A.D. Halvorson. 1991. Nitrogen fertility influence on water stress and yield of winter wheat. Agron. J. 83:1065–1070.

Nielsen, D.C., M.F. Vigil, R.L. Anderson, R.A. Bowman, J.G. Benjamin, and A.D. Halvorson. 2002. Cropping system influence on planting water content and yield of winter wheat. Agron. J. 94:962–967.

Norwood, C.A. 1999. Water use and yield of dryland row crops as affected by tillage. Agron. J. 91:108–115.

Norwood, C.A. 2000. Dryland winter wheat as affected by previous crops. Agron. J. 92:121–127.

Peterson, G.A., A.J. Schlegel, D.L. Tanaka, and O.R. Jones. 1996. Precipitation use efficiency as affected by cropping and tillage systems. J. Prod. Agric. 9:180–186.

Peterson, G.A., D.G. Westfall, and C.V. Cole. 1993. Agroecosystem approach to soil and crop management research. Soil Sci. Soc. Am. J. 57:1354–1360.

Schlegel, A.J., K.C. Dhuyvetter, and J.L. Havlin. 2003. Placement of UAN for dryland winter wheat in the central Great Plains. Agron. J. 95:1532–1541.

Schlegel, A.J., T.J. Dumler, and C.R. Thompson. 2002. Feasibility of four-year crop rotations in the central Great Plains. Agron. J. 94:509–517.

Technicon. 1973. Ammonia/BD acid digest. Industrial Method no. 321-74A. Technicon Industrial Systems, Tarrytown, NY.

Thompson, C.A., and D.A. Whitney. 1998. Long-term tillage and nitrogen fertilization in a west central Great Plains wheat–sorghum–fallow rotation. J. Prod. Agric. 11:353–359.